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Further Comparisons of Length and Voltage in the Electric Eel, *Electrophorus electricus* (Linnaeus)

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(Text-figures 1-7)

A COMPARISON of length and voltage in the electric eel, *Electrophorus electricus* (Linnaeus), has been published (Coates & Cox, 1945), but at that time only one observation on eels shorter than 40 centimeters was available. We have recently received shipments of smaller eels and it now seems worth while to supplement the earlier paper.

The new data fit smoothly into the previous curves (Text-figures 1 & 2). Although our graphs show no points for eels shorter than 10 centimeters, we did make brief qualitative observations of six fish, four to nine centimeters long. The maximum obtainable voltages ranged from 15 to 30 volts. This is within the range to be expected, as may be seen from Text-figure 2. Reliable measurements were not made, since the fish were received in poor condition and died shortly after arrival.

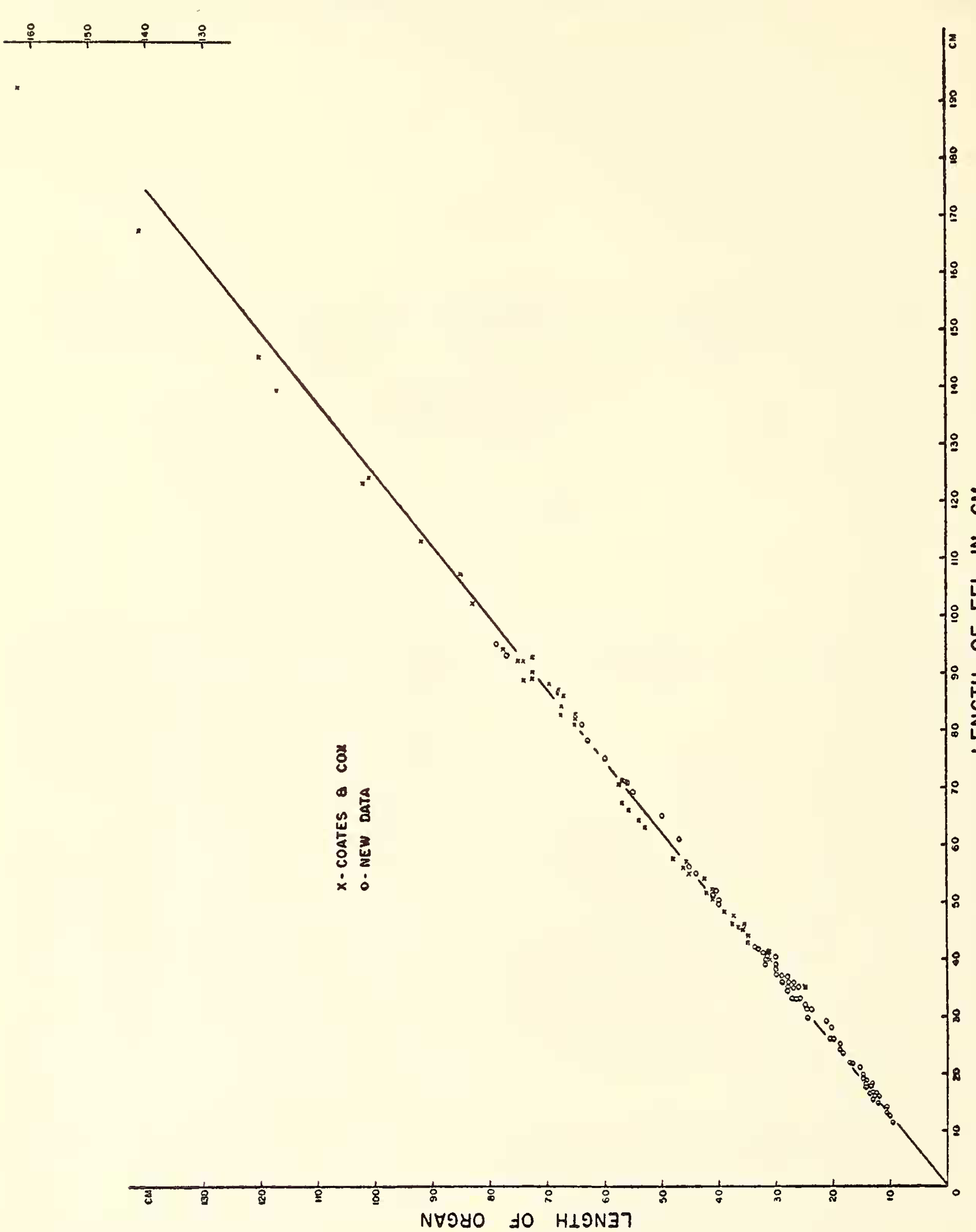
The electric eel breathes atmospheric air and may be kept out of water for extended periods of time. When taking data, we are therefore able to place the eel in a dry trough and so control the currents flowing outside its body. Metallic electrodes are pressed against the eel and leads are carried to the vertical deflection plates of a cathode ray oscillograph.

All data in this paper were taken with one electrode at the anterior end of the electric organ, the second being placed at various positions posterior to the first. No matter where the electrodes are placed, however, the anterior electrode is always positive to the posterior. Maximum voltage is obtained with 60 to 70 per cent of the electric organ between the electrodes. Including a larger fraction of the organ provides the same peak voltage but for a longer period of time. A part of the electric organ yields as large a voltage as the whole because all parts of the organ do not discharge simultaneously; excitation begins at the anterior end and progresses rapidly down the eel.

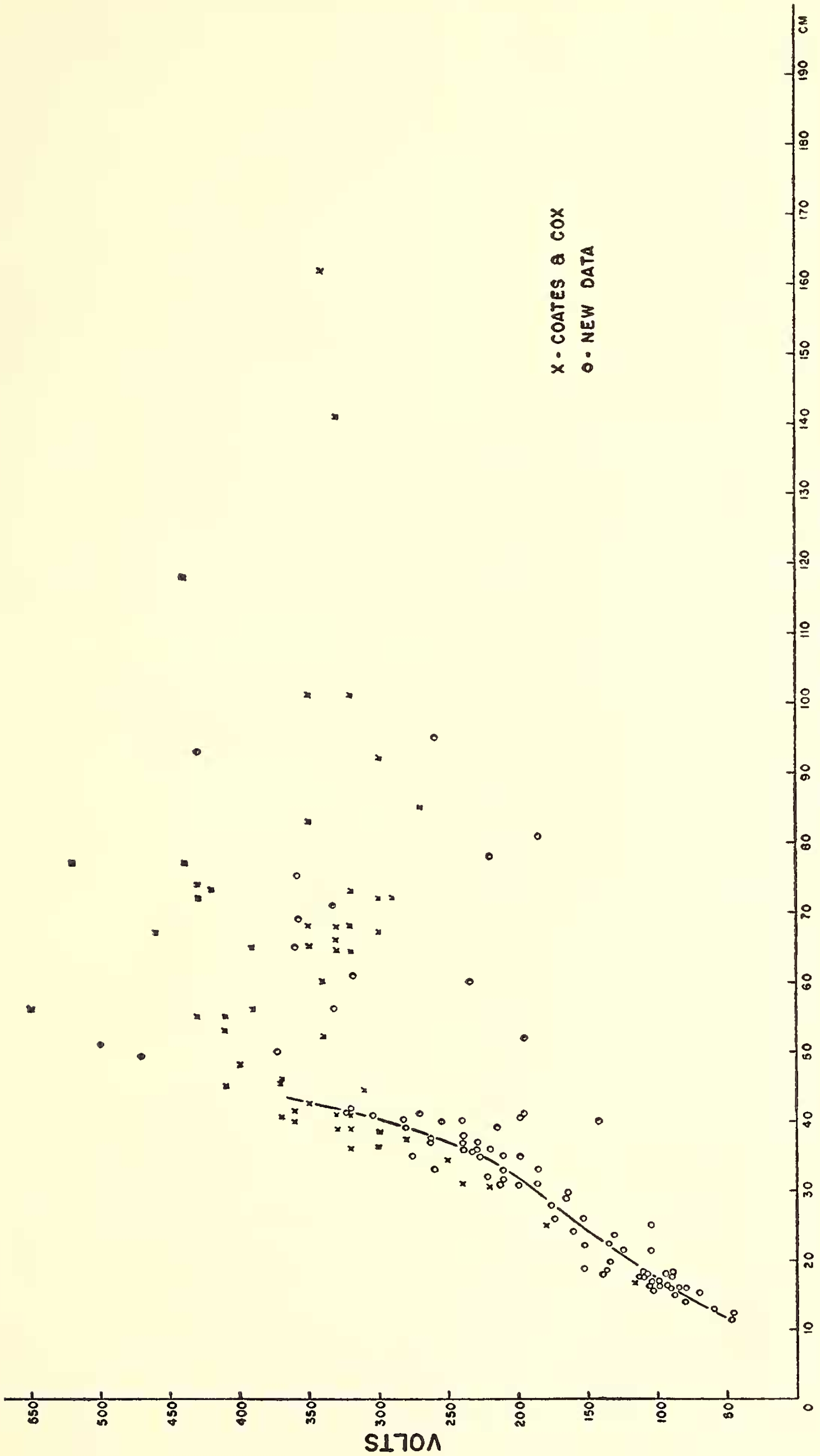
The maximum voltage per centimeter is generated by a small segment of the electric organ at the anterior end. This results partly from the lack of simultaneity noted above and partly from the decrease in number of electroplaxes per centimeter which occurs posteriorly (Cox, *et al.*, 1940). For this reason it is necessary to use electrodes separated by no more than two centimeters in measuring the maximum voltage gradient in small eels. In the case of large fish, however, the gradient across the anterior 10 centimeters is as great as that across the first two. The points of Text-figure 3 are plotted so as to distinguish between data taken with various electrode separations.

When about 50 centimeters long, eels generate their maximum voltage. We therefore take this length as marking electrical maturity. The decrease in voltage gradient for eels past this maturity has been shown to result from the fact that, as growth continues beyond 50 centimeters, the electroplaxes become thicker, so that there are fewer per centimeter of length (Cox, *et al.*, 1940).

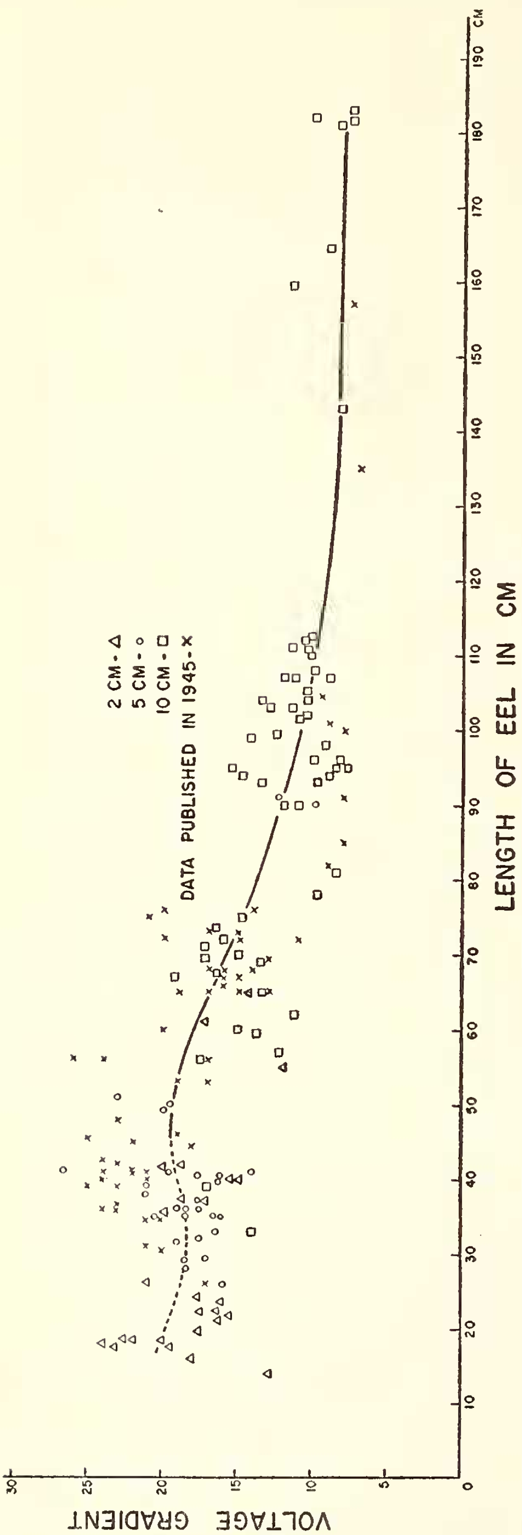
A comparison of length and electromotive force per centimeter is shown in Text-figure 4.



TEXT-FIG. 1. Length of electric eel compared with length of the large electric organ.



TEXT-FIG. 2. Length of electric eel compared with maximum voltage of entire organ.



This graph shows that the electromotive force gradient has the same dependence on length as the externally-measured voltage gradient, at least for eels longer than 60 centimeters. Unfortunately, similar data are not available for small eels. The electromotive force of eels 60 to 100 centimeters long is 20 to 50 per cent greater than the maximum external voltage. Large internal currents flowing through non-electric tissue are responsible for this.

The inter-relationship of these quantities may be understood after consideration of Text-figure 5. Text-figure 5a represents a highly simplified electrical model of an electric eel, which has nevertheless been shown to fit the data suprisingly well (Cox, Coates & Brown, 1945). In this model, E is the electromotive force, r the internal resistance of the electric tissue, and R the leakage resistance of the non-electric tissue in which the electric organ is bedded. In 5b an oscillograph has been connected. In 5c an external resistive load is shown in parallel with the oscillograph.

In 5b the voltage indicated by the oscilloscope is E′.

$$(1) \qquad E' = E \frac{R}{R + r}.$$

E′ is the voltage previously referred to as the externally measured voltage.

In 5c the voltage indicated by the oscilloscope is E″.

$$(2) \qquad E'' = E \left[1 - \frac{r}{r + \dfrac{RR'}{R + R'}} \right].$$

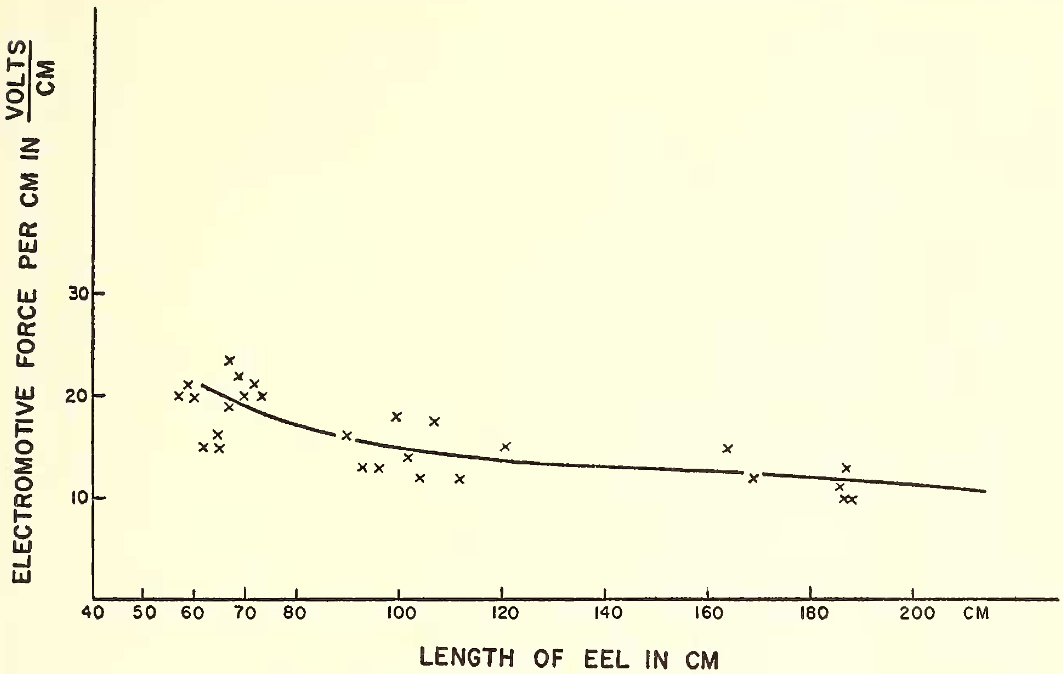
If R′ is adjusted so that

$$(3) \qquad R' = \frac{rR}{r + R},$$

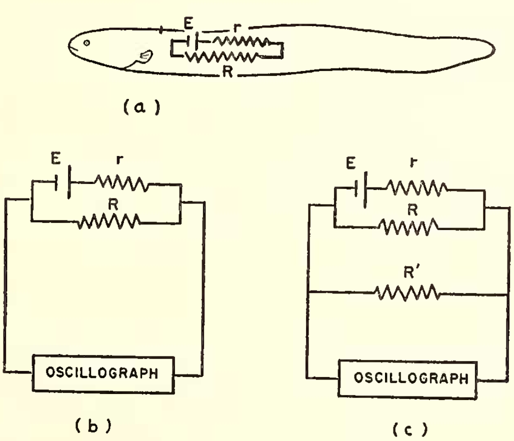
then the externally measured voltage is cut in half and $E'' = \frac{E'}{2}$ We call this particular value of the load resistance (R′) the "half deflection resistance."

The internal resistance (r) of the electric tissue and the leakage resistance (R) of the non-electric tissue for any given length should decrease as the eel grows larger and increases in girth. Therefore by the equation (3) the half value resistance (R′) should decrease with increasing length. This decrease is shown in Text-figure 6.

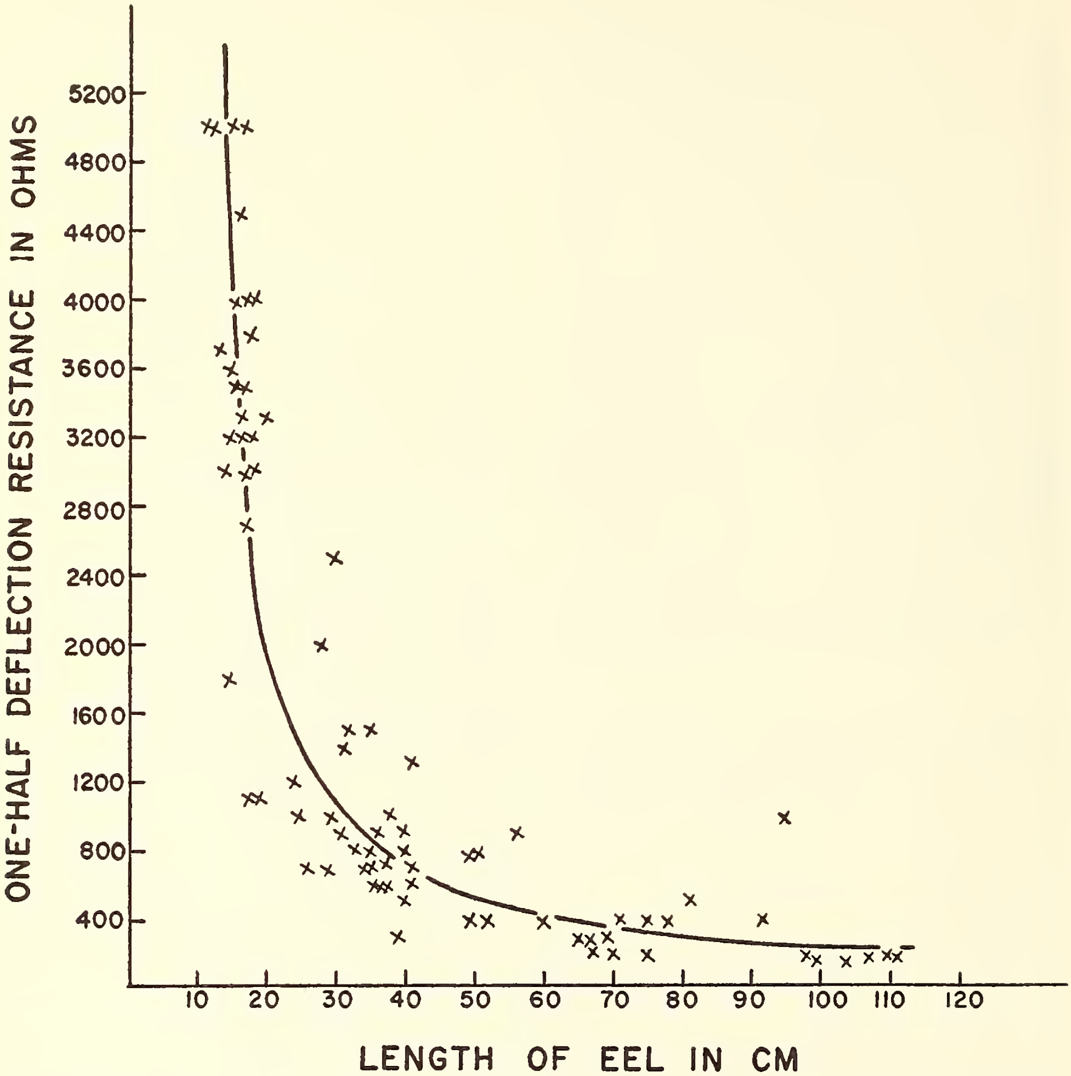
Text-fig. 3. Length of electric eel compared with voltage gradient, taken over the first two centimeters, five centimeters, and ten centimeters, of the large electric organ.



TEXT-FIG. 4. Length of electric eel compared with maximum electromotive force gradient.



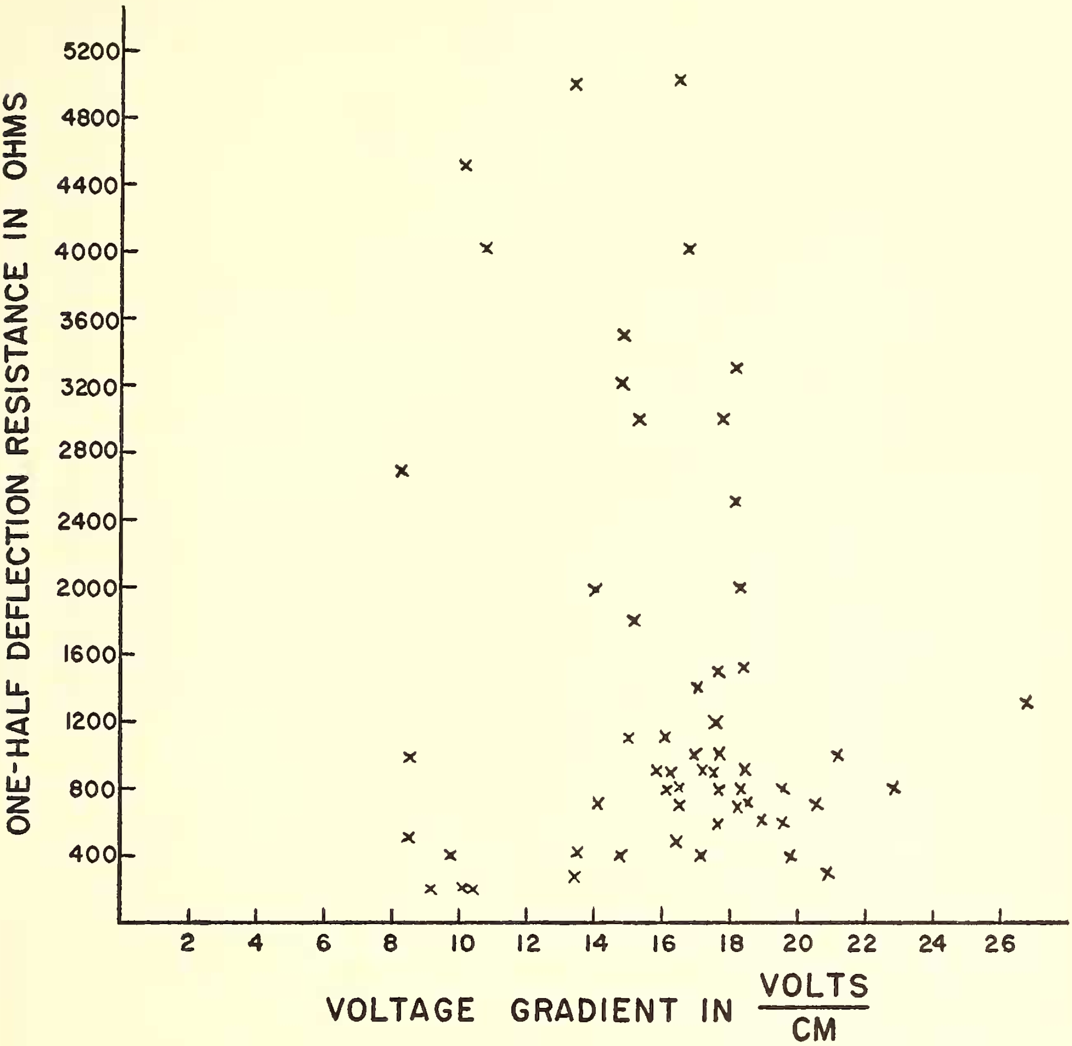
TEXT-FIG. 5. Electrical models of electric eel. a. E = electromotive force of electric organ. r = internal resistance of electric tissue. R = leakage resistance of non-electric tissue. b. Oscillograph connected to electric organ. c. Connection of a resistive load, R', to drain current from electric organ.



TEXT-FIG. 6. Length of electric eel compared with the half deflection resistance. The half deflection resistance is that external load resistance the current drain of which on the electric organ reduces the externally measured voltage by one-half. In this graph the measurements were made with the electrodes ten centimeters apart.

Text-figure 7 shows that there is little, if any, correlation between voltage gradient and half deflection resistance. An examination of equations (1) and (3) shows why: doubling the internal resistance (r) and the leakage resistance (R) doubles the half deflection resistance (R′), but does not affect the ratio of electromotive force (E) to externally measured voltage (E′).

The slight dip in the voltage gradient for eels about 30 centimeters long, shown in Text-figure 3, is reflected in Text-figure 2 as a slight change in the slope of the curve. Text-figure 3, it should be noted, is not derived from Text-figure 2. This concavity may be fortuitous and may be erased by further observations. It does not seem to be either an instrumental error or one of technique, however. Our measurements were made over a period of several months and not always with the same instruments. Moreover, the apparatus was recalibrated regularly.



TEXT-FIG. 7. Half deflection resistance compared with voltage gradient.

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